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Monitoring ocean heat content from the current generation of global ocean observing systems

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Abstract

Variations in the world's ocean heat storage and its associated volume changes are a key factor to gauge global warming and to assess the Earth's energy budget. It is also directly link to sea level change, which has a direct impact on coastal populations. Understanding and monitoring heat and sea level change is therefore one of the major legacies of current global ocean observing systems. In this study, we present an inter-comparison of the three of these global ocean observing systems: the ocean temperature/salinity network Argo, the gravimeter GRACE and the satellite altimeters. Their consistency is investigated at global and regional scale during the period 2005–2010 of overlapping time window of re-qualified data. These three datasets allow closing the recent global ocean sea level budget within uncertainties. However, sampling inconsistencies need to be corrected for an accurate budget at global scale. The Argo network allows estimating global ocean heat content and global sea level and reveals a positive change of $0.5 \pm 0.1\,\mathrm{W\,m^{-2}}$ and $0.5 \pm 0.1\,\mathrm{mm\,yr^{-1}}$ over the last 8 yr (2005–2012). Regional inter-comparison of the global observing systems highlights the importance of specific ocean basins for the global estimates. Specifically, the Indonesian Archipelago appears as a key region for the global ocean variability. Both the large regional variability and the uncertainties in the current observing systems, prevent us to shed light, from the global sea level perspective, on the climatically important deep ocean changes. This emphasises, once more, the importance of continuing sustained effort in measuring the deep ocean from ship platforms and by setting up a much needed automated deep-Argo network.

1 Introduction

Variations in the Earth's energy budget, either of natural or anthropogenic origin, have implications on changes of our climate system (Bindoff et al., 2007). Integrated time series from in situ and satellite measurements are a useful benchmark and an important diagnostic to monitor climate related changes. Following von Schuckmann and Le Traon (2011), we refer to these time-series to Global Ocean Indicators (GOIs). The planetary energy imbalance is an important measure of the changes of Earth's climate with 90 % of the increased heat flux going into the ocean to increase global ocean heat content (Hansen et al., 2005, 2011; Church et al., 2011). Global sea level rise, since it is directly related to ocean thermal expansion and the melting of glaciers and ice caps (Cazenave and Llovel, 2010; Church et al., 2011), is another important GOI. To close both, the energy and sea level budgets, one needs accurate estimations of all terms, especially the ocean component, since it is by far the largest sink of heat in the entire climate system. Observations during the era of Argo have a high potential to deliver accurate data to be used for such analyses.

Many attempts have been made to estimate interannual and long-term global ocean changes in order to better quantify the ocean's role in the Earth's energy balance, as well as to contribute to the monitoring of its current state. Identification of instrumental biases in historical in situ temperature data (Wijffels et al., 2008) and the use of Argo autonomous floats (Roemmich and Gilson, 2009) have allowed improved estimates of ocean heat content (OHC, e.g. Domingues et al., 2008; Lymann et al., 2010; von Schuckmann and Le Traon, 2011; Levitus et al., 2012), ocean freshwater content (OFC, e.g. von Schuckmann et al., 2009; Durack and Wijffels, 2010; von Schuckmann and Le Traon, 2011) and steric sea level (SSL, e.g. Willis et al., 2008; von Schuckmann et al., 2009; Cazenave et al., 2009; Leuliette and Miller, 2009; Cazenave and Lovell, 2010; von Schuckmann and Le Traon, 2011). While there was a very large spread among the earlier estimates of SSL (Willis et al., 2008; Cazenave et al., 2009; Leuliette and Miller, 2009) much of this was due to drifts and biases that have since been identified and – if possible – corrected (e.g. Barker et al., 2011; Cabanes et al., 2012).

However, significant spread among the more recent global estimates of SSL remains, which urges to an increase of our understanding of uncertainties in the ocean observing systems, including data processing, Argo sampling issues and systematic biases. In particular, the detection of systematic biases still poses a challenge for the Argo

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community as they are associated with a coherent signature over large areas and are difficult to identify with current regional quality control procedures. Moreover, this type of error has a potentially large impact on Argo GOI estimations (Willis et al., 2009; Barker et al., 2011). The comparison of Argo GOIs to other global ocean observing systems such as total sea level from altimetry, and ocean mass observations from satellite gravimetry via the global sea level budget (e.g. Willis et al., 2008) is a potential method for this kind of quality control to identify systematic biases in the global observing systems such as Argo, as well as to test the effect of Argo sampling issues on GOI estimations. However, this relies on the assumption of low systematic errors (e.g., regional biases) in either satellite altimetry or gravimetry.

Recent studies also highlight the importance of the deep ocean and undersampled regions for estimating decadal changes in Earth's radiation balance. A comparison of the Lyman et al. (2010) results with a study based on Argo float observations for the 0–2000 m layer over the period 2004–2009 indicates that a significant fraction of the warming (~ 25 %) is taking place below 700 m depth (Trenberth, 2010; von Schuckmann et al., 2009, von Schuckmann and Le Traon, 2011). Purkey and Johnson (2010) used repeat deep hydrographic sections to measure abyssal warming. They found these areas have contributed slightly less than 0.1 mm yr^{-1} to global sea level rise since the mid-1990s. A study based on three climate models find that one must integrate OHC to depths in excess of 4000 m before the gain in information with depth becomes saturated (Palmer et al., 2011). Moreover, recent studies have shown that heat is sequestered into the deep ocean during decades of large ocean-atmosphere variability, like El Niño Southern Oscillation (ENSO) variability (Roemmich and Gilson, 2011; Meehl et al., 2011), highlighting the role of interannual variability acting as precursor to sequester heat from the surface layer into the deep ocean.

Observed estimates of global OHC show significant interannual to decadal variability which makes the detection any long-term trends difficult. When time series of oceanic parameters are considered, linear trends are often computed to quantify the observed long-term changes but do not imply that the original signal is best represented by a lin-

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ear increase in time. Moreover, inter-comparisons of different GOHC estimations (e.g. Lyman et al., 2010, their Fig. 1) based on more or less the same data show substantial differences in global decadal to interannual variability. This uncertainty in variability limits our understanding of the long term trend. Analyzing the temporal evolution of GOI time series is therefore an important target to identify global imprints of interannual to decadal ocean variability on GOIs, and in turn deliver reliable interpretation of global ocean changes.

In this study we use the globally distributed Argo measurements since 2005 to investigate regional GOIs, and explore the global imprint of ocean variability. By introducing methods and tools to detect and to correct systematic errors, we propose an assessment of the estimate of GOIs, and hence, improve our capability to monitor climate related changes. The results of our study contribute to the understanding of the budget contributions from a global perspective. In Sect. 2, the data sets and error estimations are described. Results for global OHC and global SSL are presented, together with the global sea level budget. In Sect. 4, the sea level budgets for three ocean sectors are analysed. Our findings are discussed in Sect. 5.

2 Data

GOIs associated to OHC and SSL are evaluated using a weighted box averaging scheme of Argo data as described in von Schuckmann and Le Traon (2011). A reference depth of 1500 m is chosen as the number of profiles in the 1500–2000 m depth layer is significantly less than within 0–1500 m before year 2009 (Cabanes et al., 2012, their Fig. 7). The Argo profiles undergo re-qualified data validation methods using a tool developed by Gaillard et al., 2009 (see also von Schuckmann et al., 2009). Black-listed profiles and platforms are excluded from the data set. Every profile on alert has been checked visually which allows excluding spurious data (e.g. data drift). This procedure minimizes systematic biases in the global Argo data set as discussed by Barker et al. (2011). Error bars represent one standard error, accounting for reduced degrees

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of freedom in the mapping and uncertainty in the reference climatology as described in von Schuckmann and Le Traon (2011).

Argo data are compared with measurements from two independent global observing systems. Variations in the mass component of sea level are computed using observations from the Gravity Recovery and Climate Experiment (GRACE). We use the most recent Release_05 data processed by the University of Texas Center for Space Research (Bettadpur, 2012), modified to correct deficiencies in the geocenter and $C_{2,0}$ coefficient as described by Chambers and Schröter (2011). The average bottom pressure (in terms of equivalent sea level) over specific regions is computed for each month using the averaging kernel method (Swenson and Wahr, 2002). Argo coverage and altimetry product quality fall off rapidly poleward of ±60° latitude. We therefore limit our study ±60° latitude and consequently define GRACE data averaging kernel over this specific areas of interest. Land and ocean areas within 300 km of land are also excluded from the averaging kernel to minimize leakage from land hydrology and ice sheets (Chambers, 2009). The actual output from the calculation is the average ocean bottom pressure for the region, which includes both the average ocean mass component and a small, but non-negligible contribution from the time-variable average atmospheric pressure over the entire ocean basin. To compute the mass component for use in the sea level budget, this pressure signal must be subtracted for each month, which we do using data from the European Center for Medium-range Weather Forecasting (ECMWF) that is distributed with the GRACE products (Willis et al., 2008).

GRACE measurements also require a correction for glacial isostatic adjustment (GIA) that is considerably larger than that used for altimetry. Although two very different corrections exist in the literature (derived from Peltier, 2009; Paulson et al., 2007), both are based on the same ICE5G ice history (Peltier, 2004) and on similar mantle viscosity profiles. It has recently been discovered that GRACE GIA correction proposed in Peltier (2009) was in error, as first suggested by Chambers et al. (2010). Peltier et al., 2012 (see also, Chambers et al., 2012) have confirmed there was a mistake in their code, so that now the two corrections are consistent. It is important to note, however,

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that a single value for a GRACE GIA correction cannot be used, as it is dependent on the averaging kernel utilized (Chambers et al., 2010) and is also likely uncertain at the ±30 % level due to considerable uncertainty in past ice loading histories over North America and Antarctica as well as uncertainty in mantle viscosities. This uncertainty is equivalent to ±0.3 mm yr^{-1} of global ocean mass, and varies widely over regional scales (30S–30N: ±0.4 mm yr^{-1}; 30N–60N: ±0.6 mm yr^{-1}; 60S–60N: ± 0.3 mm yr^{-1}). This uncertainty is included in the trend estimates of the presented study (by adding in as a Root-Sum-Square, RSS), and the correction is based on convolving the Paulson et al. (2007) GIA model with the exact averaging kernel applied to the GRACE observation. We estimate monthly uncertainty from the diagonal covariance matrix, which we calculate using values distribute with the GRACE coefficient (Swenson and Wahr, 2002) and we also include error from land and ice sheet (leakage estimated from model simulation of Chambers (2009); standard error is 1.7 mm for the average over 60° S–60° N, 4 mm for 30° S–60° S, 3 mm for 30° S–30° N, and 6 mm for 30° N–60° N).

Sea level anomalies are computed from the delayed-mode AVISO gridded merged data product (SSALTO/DUACS, www.aviso.oceanobs.com), based on multiple satellite altimeters. GIA affects altimetry differently than it does for GRACE, being related to the rate of change of the sea floor due to GIA, not the gravity response. It therefore has a much smaller size, and has been estimated to be ± 0.3 mm yr^{-1} over 60° S to 60° N (Peltier, 2004). The value does differ slightly for sub-regions, and has been calculated to be ±0.2 mm yr^{-1} for the 30° S–30° N area, ±0.4 mm yr^{-1} for the 30° N–60° N area, and ± 0.3 mm yr^{-1} for 30° S–60° S, all based on the ICE5G-VM2 model provided by Peltier (2004). These trends are applied to each regional average, and are also assumed to have an uncertainty of 30 %. The uncertainty on the trend estimated from altimetry are inflated by ±0.4 mm yr^{-1} for every region to account for uncertainty in the drift determination of the altimeter and important corrections like the water vapor radiometer (Ablain et al., 2009; Meyssignac and Cazenave, 2012), as well as the uncertainty in GIA correction.

3 Global ocean indicators

3.1 Global ocean heat content and steric sea level from Argo

The time series of global OHC and global SSL for the period 2005 to 2012 are shown in Fig. 1. The time-series are associated with a 8 yr trend of $0.5 \pm 0.1\,\mathrm{W\,m^{-2}}$ and $0.5 \pm 0.1\,\mathrm{mm\,yr^{-1}}$, respectively. Estimates of von Schuckmann and Le Traon, 2011 show consistent results for global OHC ($0.5 \pm 0.1\,\mathrm{W\,m^{-2}}$) for the 2005–2010 period. For global SSL, the 8-trend is actually weaker than the previously computed 6 yr trend ($0.75 \pm 0.2\,\mathrm{mm\,yr^{-1}}$; von Schuckmann and Le Traon, 2011), but are still consistent within their error margin. We believe that the strong interannual signature of El Niño Southern Oscillation (ENSO) variability in the tropical Pacific during the end of the 2010 and during 2011 affects the short-term trend estimate (Fig. 1b).

A similar signature of ENSO is observed in global mean sea level from satellite altimetry. The sea level in the period of satellite observations (1993–2012) increased at an average rate of $3.2 \pm 0.5\,\mathrm{mm\,yr^{-1}}$ (Meyssignac and Cazenave, 2012), but shows a slower rate during the Argo era of $2.0 \pm 0.5\,\mathrm{mm\,yr^{-1}}$ (e.g. Hansen et al., 2011). Based on the existing correlation between global sea level and ENSO (Nerem et al., 2010), it has been suggested that the recent slower rate of sea level rise may in part be due to the strong La Niña in 2010/2011. One characteristic of ENSO variability is its associated vertical redistribution of heat: warmer surface layers of the El Niño phase cause a loss of ocean heat content and, opposite effect during La Niña events (Roemmich and Gilson, 2011). Although the 2010–2011 La Niña event does show a strong signature on the global heat content time-series (Fig. 1a), it does shows up in the steric sea level times-series.

Another characteristic of ENSO event is its associated anomalous storage of water on continents during La Niña related to precipitation changes, which causes both a large drop in the ocean mass (Llovel et al., 2011; Cazenave et al., 2012; Boening et al., 2012), but also a smaller decrease in halosteric sea level. In agreement with this importance of water storage and salinity anomaly, we find a large signature in freshwater content, and hence in the halosteric component which, in turn, partly counterbalances the thermosteric component in the tropical ocean (not shown). Consistently, it has been found that the slower rate of sea level rise during 2005–2010 can only be reconciled using steric height variability computed from Argo data that includes salinity (as opposed to XBT data) (Llovel et al., 2011). Recent up-dated time series of global mean sea level show that the 2005–2010 slowdown was only temporary and that global sea level has recovered a mean rise of 3.2 mm yr^{-1} (www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/ and www.columbia.edu/~mhs119/SeaLevel/).

3.2 The global sea level budget

Global sea level change SL_{TOTAL} is related to global steric height time-series (SL_{STERIC}) and mass variability (SL_{MASS}) through:

$$SL_{TOTAL} = SL_{MASS} + SL_{STERIC}(\text{Argo}) + SL_{RES}$$

(SL = sea level, e.g. Willis et al., 2008; Leuliette and Miller, 2009). The residual of the sea level budget (SL_{RES}) includes deep ocean steric changes below 1500 m depth (i.e. depth below Argo coverage), plus any source of uncertainty in observations and/or data treatment. In this section, we present results averaged for the entire region extending from 60° S to 60° N, which we will, hereafter, refer to as the global ocean estimate.

We seek to estimate the residual, SL_{RES}, using three major global observing systems: SL_{TOTAL} is computed from altimetry products (AVISO), SL_{MASS} from satellite gravimetry (GRACE), and SL_{STERIC} in the upper 1500 m from temperature and salinity observations from Argo. Beside signature of deep ocean change, other information can be drawn from the inter-comparison of these three global ocean observing systems. Namely, a SL_{RES} unequal to zero can relate to systematic observation biases, data processing uncertainties, sampling array issues, etc.

The error bar of SL_{RES} is derived from the residual sum of squares of the errors of the three time series, assuming that the three time series are independent. This is not exactly true as the GIA corrections for altimetry and GRACE are derived from the same ice history (see Sect. 2), but the manner of the correction is quite different. Still, some common errors could potentially cancel, but we account for this in increasing the trend error from the fit with the uncertainty in GIA as described in Sect. 2. Trends of SL_{RES} are calculated using a weighted least square fit taking into account the error bar of the time series as described in the appendix of von Schuckmann and Le Traon (2011). Unless otherwise stated, the error bars reflect one standard error and account for (i) GIA and drift uncertainty in GRACE and altimetry by computing the residual sum of squares of the standard error in the fit, (ii) the GIA error from GRACE, and (iii) the drift error for altimetry.

Figure 2a shows the residual SL_{RES} computed by averaging the full gridded altimetry product over the global ocean (i.e. 60° S–60° N). The global residual shows a slight and non-significant positive trend of $0.3 \pm 0.6\,\mathrm{mm\,yr^{-1}}$. The global sea level budget over 60° S–60° N can therefore be closed within error bars for the years 2005–2010. However, one possible large source of uncertainty is the inconsistency between Argo sampling and sampling from satellite-derived products (altimetry and gravimetry). Indeed, Argo has much coarser resolution than the satellite systems and can therefore alias regional signals. To test the sensitivity of GOIs to this sampling issue, we next subsample altimeter data on position and time of Argo profiles. Global mean SL_{TOTAL} is then recomputed following the procedure von Schuckmann and Le Traon (2011).

Estimate of SL_{RES} using subsampled altimetry fields ($[SL_{RES}]_{sub}$ hereinafter) are shown for the global ocean in Fig. 3a. The differences in trends between the global ocean calculation in Figs. 2a and 3a are not significantly changed. Although the sign of the residual trend changes sign, the magnitude is still within the calculated standard error ($-0.6 \pm 0.6\,\mathrm{mm\,yr^{-1}}$). Therefore, at global scales, systematic observation biases, data processing uncertainties and sampling array issues lie within error bars. Moreover our results indicate that the global observing systems are consistent at global scale, and hence global scale ocean state analyses appear to be robust. However, although changes observed in Figs. 2a and 3a are not significant, it is important to understand them, which lead us to extend our assessment of Argo GOIs also to regional scales.

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4 The sea level budget in three ocean sectors

Analyses of ocean hydrological properties are carried out in three sectors of the world oceans: the Northern Ocean (NO) defined as the ocean sector extending from 30° N to 60° N, the Tropical Ocean (TO) from 30° S to 30° N and the Southern Ocean (SO) from 30° S to 60° S. This regional partition differs from previous works where a more classical separation in three major ocean basins (Atlantic, Pacific and Indian) is often used. We believe that the geometry used here allows us to distinguish between regions where different processes are at work: the NO is opened to the highest latitudes in the Atlantic with significant water mass exchanges with the Arctic and from Greenland ice melt, the TO is known to have faster dynamics and climate signals related to El Niño, La Niña, and the Indian Ocean Dipole, while the SO is the only basin with a continuous and deep current associated to intense zonally banded atmospheric forcing, and is also subject to significant ice melt from Antarctica.

4.1 The tropical ocean sector

In the TO sector between 30° S–30° N, the regional sea level budget has a significant positive trend of $1.6 \pm 0.7\,\mathrm{mm\,yr^{-1}}$ (Fig. 2b). Hence, the regional sea level budget in the TO sector is far from being closed, indicating unresolved systematic errors in one or more of the observations. The sensitivity of the sea level budget to Argo sampling issues as described in the previous sections is tested for this ocean sector. Residual trend in the TO sector strongly reduces when using consistent sampling for altimetry and Argo (Fig. 2b versus Fig. 3b; residual trend reduced to $0.2 \pm 0.7\,\mathrm{mm\,yr^{-1}}$). We can hence close the regional sea level budget in the TO sector but only when correcting for inconsistent data sampling.

Figure 4 shows maps of regional 2005–2011 trends for SL_{TOTAL} (panel a) and SL_{STERIC} (panel b). Consistent with the large trend difference that we found between SL_{RES} to $[SL_{RES}]_{sub}$, we find the largest differences between SL_{TOTAL} and SL_{STERIC}

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in the TO, in the Indonesian Archipelago, where almost no Argo measurements exist. Surprisingly such small region has a dramatic effect on the global or TO average.

The sensitivity of sampling issues in the Indonesian Archipelago on the global mean sea level is tested and shown in Fig. 4c. For this purpose, global SL_{TOTAL} is calculated, ignoring measurements in the Indonesian Archipelago box (Fig. 4c, blue line), and compared to the complete global SL_{TOTAL} time series (black line). The results show that ignoring sea level changes in the Indonesian Archipelago reduces global total sea level rise by 20 % during the years 2005–2011, and by 7 % during the entire altimeter era 1993–2011.

4.2 The Northern Ocean sector

In the NO sector, the residual of the regional sea level budget has a significant negative trend of $-3 \pm 0.9\,\mathrm{mm\,yr^{-1}}$ (Fig. 2c), which makes it the region of the largest residual trend. This residual trend is partly explained by sampling issues as $[SL_{RES}]_{SUB}$ reduces to $-2.1 \pm 0.9\,\mathrm{mm\,yr^{-1}}$ (Fig. 3c). Nevertheless, the negative residual trend in the NO sector remains significant even when correcting for sampling inconsistency.

The difference between $[SL_{TOTAL}]_{sub,}$ SL_{STERIC} and SL_{MASS} is particularly large during the beginning of the time series (2005–2006) in the NO sector (Fig. 5). This discrepancy induces a strong difference in the trend estimate of the different time series, and the residual shows therefore a large non-zero trend (Fig. 3c). Although using subsampled altimetry reduces the differences slightly, it does not remove the problem. Previous studies have shown that abyssal thermosteric changes are small, and even negative in the North Pacific (Purkey and Johnson, 2010). Deep ocean steric change is therefore very unlikely to cause the observed negative residual trend. Studies in a smaller region of the North Pacific, however, finds very good agreement in trends of ocean mass and steric-corrected altimetry (Chambers, 2011). The region in that study, though, is an area with very large dynamical adjustments in ocean mass and is away from the large mesoscale variability of the western boundary currents.

Our sampling tests, based on mapped altimetry, may still not adequately account for the true sampling of mesoscale eddies in the Kuroshio and Gulf Stream that would be seen in the Argo measurements. Further work using high resolution, eddy-resolving models will be needed to test whether sampling of eddies is responsible for the problem in the NO. However, we note that the area covered by the NO is less than 10 % of the total area of the global ocean, so this apparent regional systematic error or sampling problem does not significantly affect the global residual analysis.

4.3 The Southern Ocean sector

In the SO area, the regional sea level budget is closed within error bars, with a residual trend of $-0.7 \pm 0.7\,\mathrm{mm\,yr^{-1}}$ (Fig. 2d). Variations of Argo sampling as a function of time are largest in the SO region, even during the recent Argo period 2005–2010 (von Schuckmann and Le Traon, 2011, their Fig. 1c). Estimates of $[SL_{RES}]_{SUB}$ are shown in Fig. 3d for the SO area. Using consistent sampling for altimetry and Argo, the observed negative bias in the SO sector becomes significant ($-1.5 \pm 0.7\,\mathrm{mm\,yr^{-1}}$). Interestingly, the residual trend actually increases when correcting for sampling inconsistency (Fig. 3d). Previous studies have presented rapid and dramatic deep Southern Ocean changes, below the depth covered by the Argo array, which would arguably cause a residual trend (e.g. Purkey and Johnson, 2010). However, these deep ocean changes would be associated with a positive residual trend (associated with deep ocean warming and/or freshening). Unfortunately, we can conclude here that uncertainties in the observing systems seem still too large to allow detection of deep ocean temperature and salinity change below 2000 m depth via the regional and hence, global sea level budget.

The difference between $[SL_{TOTAL}]_{sub}$, SL_{STERIC} and SL_{MASS} is systematically large during the end of the time series (2009–2010) in the SO sector (Fig. 6a). This discrepancy induces a strong difference in the trend estimate of the different time series, and the residual shows therefore a non-zero trend (Fig. 3d). However, the strong signature of SO interannual variability in sea level is forced by both ocean mass and steric

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changes (Fig. 6a). The water column comprised between 10–1500 m in the SO undergoes deep reaching variability of heat (Fig. 6b) and freshwater content (Fig. 6d), in particular during the 2009–2010 period (and 2011, not shown). These deep reaching events could potentially have important climate implications and deserve a full study by themself, which is beyond the scope of the present paper. However, we note that two main mechanisms could explain these large anomalies: (i) anomalous convection events in mode and intermediate waters (e.g. Herraiz and Rintoul, 2011; Naveira-Garabato et al., 2009); (ii) interannual variability in ACC front position and associated subtropical gyre extent (e.g. Roemmich et al., 2007; Sallée et al., 2008; Sokolov and Rintoul, 2009). These Southern Ocean heat content anomalies are actually dominated by anomalies centered on 40–50° S (not shown), advocating for a dominance of the latter process.

However, we note that the year 2010–2011 was characterized by a large positive anomaly of the Southern Annular Mode, which is associated with a southward contraction and intensification of the Southern Hemisphere Subantarctic atmospheric jet (e.g. Thompson et al., 2011). Positive anomaly of this climate mode has been shown to be associated with a southward shift of ACC fronts, consistent with a positive heat content anomaly and sea level rise (Sallée et al., 2008; Sokolov and Rintoul, 2009).

5 Discussion

A combination of global in situ temperature and salinity measurements from Argo, total sea level from satellite altimetry and ocean mass from GRACE are analysed in this paper from an Argo perspective. The up-dated Argo GOIs for the period 2005–2012 reveal an increase of $0.5 \pm 0.1\,\mathrm{W\,m^{-2}}$ for GOHC and $0.5 \pm 0.1\,\mathrm{mm\,yr^{-1}}$ for GSSL over 8 yr. Significant interannual GSSL fluctuations largely impact the estimate of short-term trend. We attribute much of the interannual variability to tropical OFC changes, rather than to OHC fluctuations. However, we show that the global sea level budget can be closed for the period 2005–2010 within error bars. We identified a systematic

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bias introduced by coarse Argo sampling in some parts of the TO sector, in particular in the Indonesian Archipelago region. However, even when correcting for this sampling issue, although the systematic bias is reduced, a significant bias remains, either from data processing methods, or systematic errors in altimetry or gravimetry data. This is most highlighted in the NO sector. The analysis highlights however the importance of correcting for sampling inconsistency when estimating sea level budget, especially in the TO sector. Systematic biases due to instruments fail functions can also introduce biases in global estimate as shown in previous analyses (e.g. Barker et al., 2011).

Trends in GOIs over short periods (typically less than 10 yr) are very sensitive to interannual variability that can regionally be very large. Therefore, if we are to detect rapid climate change from GOI using the current global observation network, it is important to pursue strong effort in analyzing and detecting the sources of GOI uncertainties, and particularly their variability.

Deep ocean steric changes are large in the SO sector (e.g. Boening et al., 2008; Leuiliette and Miller, 2009; Sutton and Roemmich, 2011). Consistently, about half of the hemispheric total sea level rise has been found to be steric over decadal scale, with this proportion increasing southwards (Sutton and Roemmich, 2011). However, our results confirm that uncertainties in the current observing network are still too large to allow detection of deep ocean change (below 2000 m depth) from a global sea level budget. We can observe a significant trend in our results of the residual of the sea level budget. If the errors associate with the current observation networks stay constant (i.e. standard errors shown in Fig. 3d), the deep steric trend would have to be greater than 0.4 mm yr^{-1} for 15 yr to be able to be detected at the 90 % confidence level. However, with increasing numbers of Argo floats in the SO, and assuming continued altimetry and gravimetry, we may hope to be able to start detecting subtle and climatically important deep ocean change in the future. However we want to stress here than even a very good sampling in the first 2000 m of the ocean will never replace the need of accurate deep ocean temperature measurements to detect subtle change and possible acceler-

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ation of change. This emphasises once more the importance of deep measurements, such as from ship or from deep Argo probes.

The estimation of Argo GOIs, its related short-term trends and the calculation of the global sea level budget in this study aim at giving way to increase the quality and confidence on global climate indicators from in situ observations. Knowing its uncertainties will also help to interpret comparisons to global ocean synthesis products for validation purposes. Confidence in the results will become high only if all issues are well understood. The findings of this study will contribute to prepare Argo for future monitoring of long-term climate trends of high accuracy much needed for monitoring of the state and changes of the ocean's component of our Earth's climate system.

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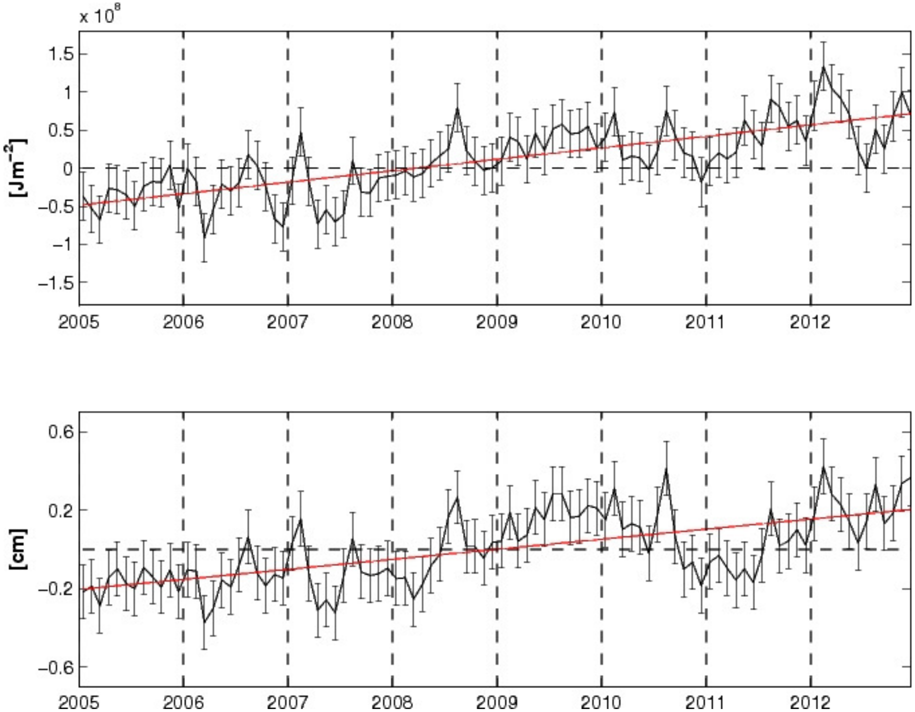

Fig. 1. Up-dated global ocean (60° S–60° N) heat content (upper, GOHC) and steric sea level (lower, GSSL) during 2005–2012 from Argo after the method of von Schuckmann and Le Traon, 2011. 8 yr trends (red line) of GOHC/GSSL account for $0.5 \pm 0.1\,\mathrm{W\,m^{-2}}$, and $0.5 \pm 0.1\,\mathrm{mm\,yr^{-1}}$ for the 10–1500 m depth layer, respectively. Error bars are due to data processing and climatology uncertainties, but do not include systematic errors.

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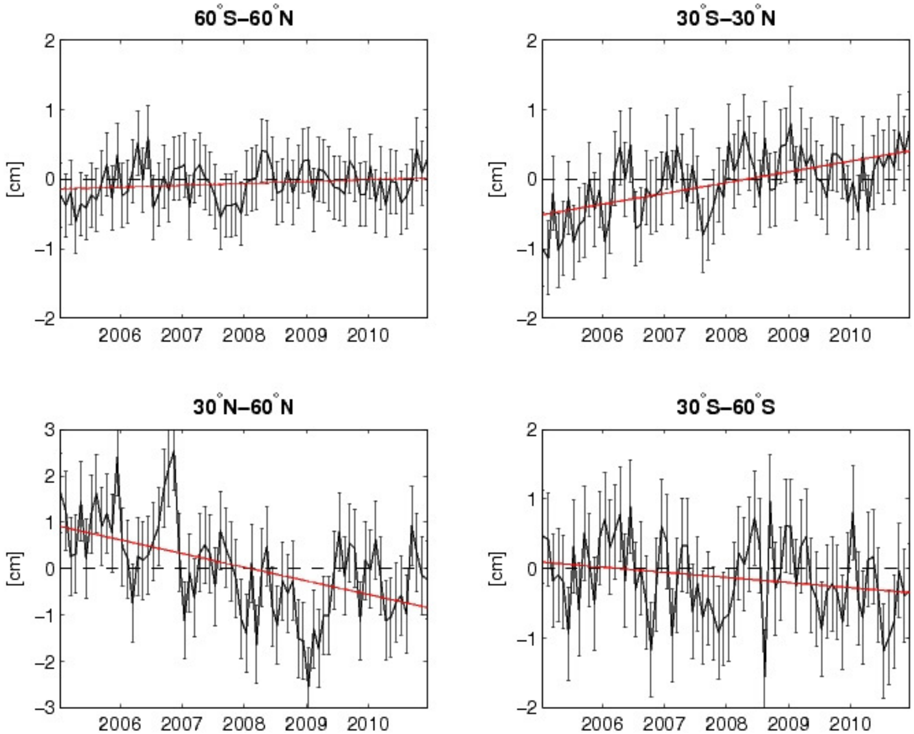

Fig. 2. Residual of the sea level budget at different latitude bands using Argo steric sea level (Fig. 3a, red), AVISO delayed mode gridded fields and GRACE data. Residual trends amount to $0.3 \pm 0.6\,\mathrm{mm\,yr^{-1}}$s for the global ocean, $1.6 \pm 0.7\,\mathrm{mm\,yr^{-1}}$s for the tropical ocean, -3 ± 0.9 for the northern ocean, and -0.7 ± 0.7 for the southern ocean. See text for more details on data, method and error estimation.

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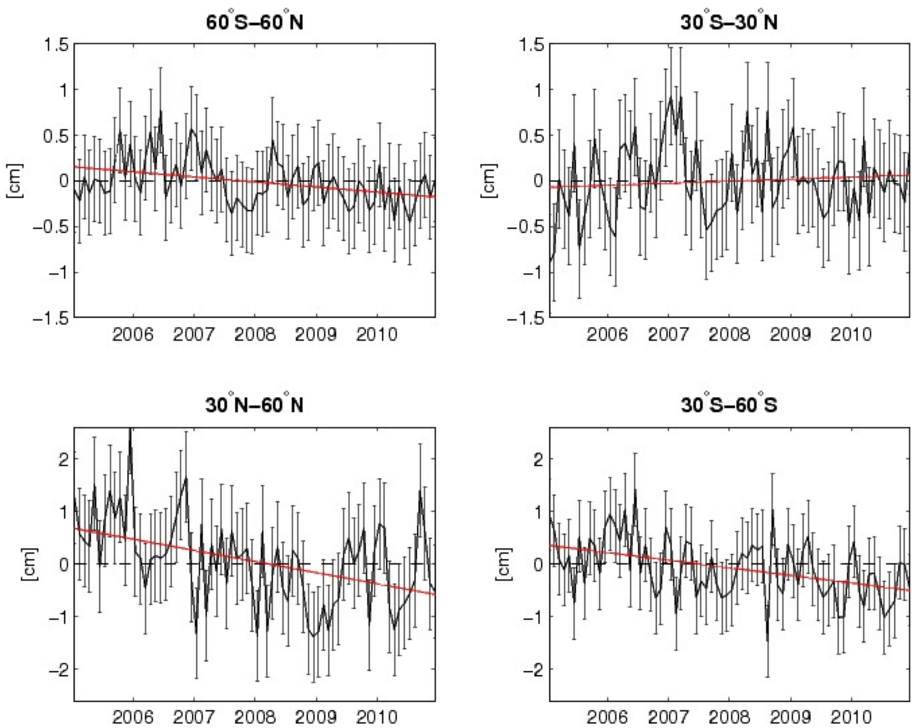

Fig. 3. Same as Fig. 5, but using sampled Altimeter data to monitor the effect of Argo sampling (see text for more details). Residual trends amount to $0.6 \pm 0.6\,\text{mm yr}^{-1}$s for the global ocean, $0.2 \pm 0.7\,\text{mm yr}^{-1}$s for the tropical ocean, -2.1 ± 0.9 for the northern ocean, and -1.5 ± 0.7 for the southern ocean. See text for more details on data, method and error estimation.

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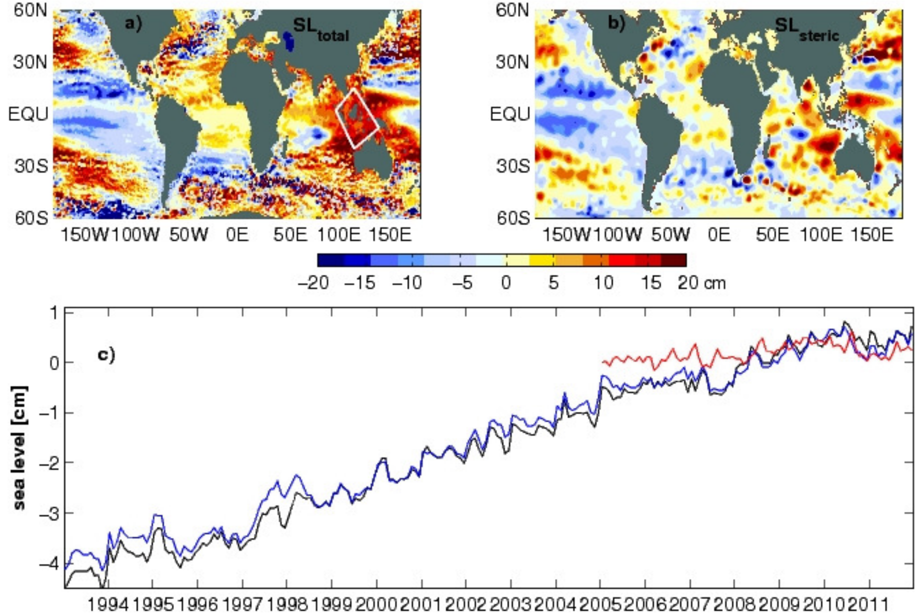

Fig. 4. Map of 7 yr trends (2005–2011) of **(a)** total sea level from AVISO and **(b)** steric sea level (10–1500 m) based on in situ data (ARIVO gridded field, http://wwz.ifremer.fr/lpo/SO-Argo/Products/Global-Ocean-T-S). **(c)** Global mean total (black) and steric (red, Fig. 3) sea level, together with global total sea level where data in the Indonesian Archipelago have been ignored (blue line). Box of the Indonesian Archipelago test (see text for more details) is added in **(a)**.

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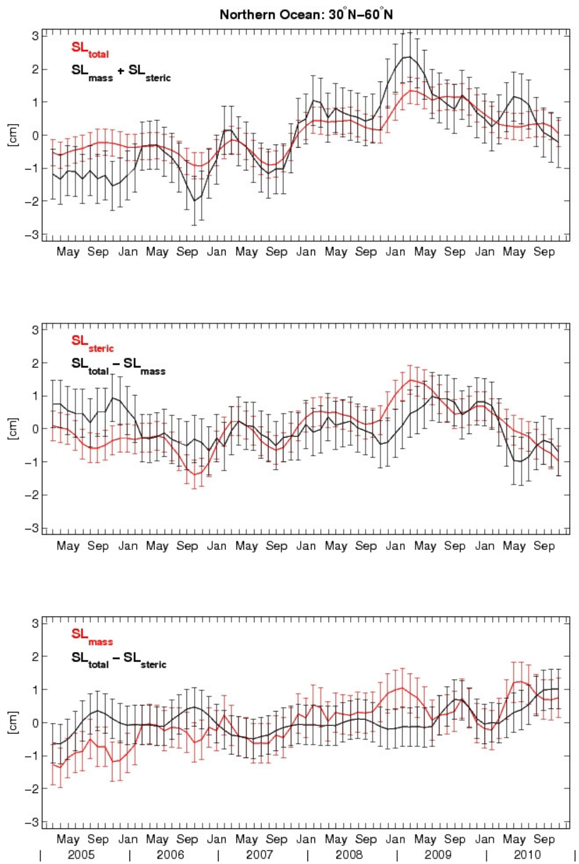

Fig. 5. Different components of the sea level budget averaged for the 30° N–60° N latitude band during the period 2005–2010 and smoothed using a 3 monthly running mean. Compared are directly derived components from the observing systems (red) compared to the inferred ones (black), respectively. For total sea level, $[SL_{TOTAL}]_{SUB}$ is used (see text for more details).

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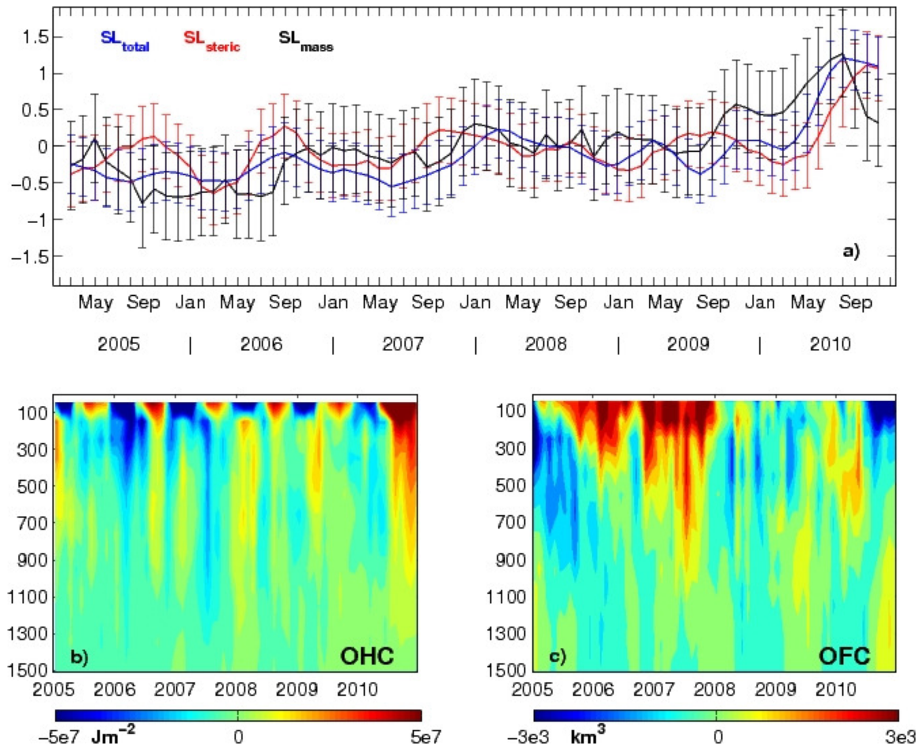

Fig. 6. (a) Single components of the sea level budget from altimetry (blue), Argo (red) and GRACE (black) measurements averaged over the 30° S–60° S latitude band for the period 2005–2010 and smoothed using a 3 monthly running mean. For total sea level, $[SL_{TOTAL}]_{SUB}$ is used (see text for more details). **(b)** Ocean heat content (OHC) and **(c)** ocean freshwater content (OFC) as a function of depth during 2005–2010, averaged over the same latitude belt.

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